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METHOD AND APPARATUS FOR GRINDING

The invention concerns a method and apparatus for grinding. In particular, it relates to an improvement in a process called creep-feed grinding by means of which a very high material removal rate ("MRR") is achieved.

The invention is particularly useful in removing material for particularly difficult to machine materials, for example, titanium alloy. The known processes of removing material are conventionally achieved by milling or broaching. However, each process has particular disadvantages for example, when milling titanium alloys the cycle time is relatively long and the consumable cost per item is increased because the milling cutter itself machines relatively few parts before requiring refurbishment. Therefore, the geometrical quality can sometimes be affected, particularly when dealing with complex forms.

The use of broaching materials such as titanium alloys is more common but there are significant set-up costs and refurbishments costs. Furthermore, the component can be subjected to higher cutting forces during removal of the materials.

It is known to grind tough materials, but only when there is a very small amount of material to be removed. Such a grinding process uses a silicon carbide abrasive wheel type to grind the component at very low removal rates and is, therefore, considered to be suitable only as a finishing process because the cycle times would be prohibitive for any other use.

One of the current major grinding difficulties in present times centres on the coolant nozzle setup, adjustability and design for a range of grinding wheel profiles. This is normally complex and unreliable.

US-A-5, 826, 478 (Zerrer) discloses a hand held, powered cutting tool incorporating a single nozzle for supplying liquid to the external surface of the rotating cutting wheel. Being hand held, the disclosed device is not amenable to precision grinding, and coolant water supplied will be at comparatively low flow and pressure. No provision is made either for changing profile of the cutting wheel or for any automated tool change in use.

EP-A-0924 028 (Rolls Royce) is concerned with an apparatus and method for creep-feed grinding wherein a conventional porous abrasive grinding wheel is used in combination with an applied jet of high pressure coolant directed to an exterior surface of the wheel. The high pressure jet is used for simultaneous cooling of the wheel and workpiece and cleaning of the wheel whereby ground material debris is removed from the abrasive surface particles. Depending upon the position of the workpiece the jet nozzle has to be moved.

EP-A-0 903 200 (Unova) disclose grinding apparatus adapted to grind crankshaft crankpins, provided with a single external coolant nozzle with variable pressure but which is unable to clean the grinding wheel surface. No provision is made for automated tool change.

US-5 961 376 (Gottschald) is concerned with increasing the service life of a grinding wheel by applying low and high pressure coolant intermittently during the grinding process. No provision is made for automated tool change.

EP-0581 507 (Ford) discloses a grinding wheel assembly particularly adapted to the grinding of glass material. The assembly relies upon centrifugal force to accelerate flow of coolant and an arrangement of troughs to guide the coolant to the required areas. In use, the wheel assembly tends to clog and hence requires cleaning. An external cleaning jet is not present and no provision is made for automated tool change.

The inventors have gone against conventional thinking by producing a high speed grinding apparatus, which overcomes, or at least mitigates the problems of the prior art.

According to a first aspect of the present invention there is provided apparatus for high speed grinding comprising a diamond bonded abrasive wheel, drive means for mounting and rotating the grinding wheel at peripheral speeds up to about 200 m/s, and a liquid coolant supply system including delivery means for directing liquid coolant to the point of grinding contact.

According to an optional feature of this embodiment the delivery means is a nozzle arranged to direct a jet of liquid coolant at the point of grinding contact in a direction substantially tangental to the wheel.

Alternatively, delivery means is provided through the grinding wheel, which delivery means comprises a plurality of channels for connecting an interior chamber to the exterior surface of the grinding wheel.

In some embodiments, the plurality of channels is provided by radial slots formed in the grinding wheel. Preferably, the liquid coolant is supplied to the chamber. More preferably, the liquid coolant supplied to the internal chamber is directed within the chamber by guide means towards the point of grinding contact.

According to another optional feature of this aspect of the invention, there further comprises a second nozzle to direct a jet of liquid coolant to the periphery of the wheel to clean the wheel surface.

In one class of embodiments, the liquid coolant supply system in use, delivers liquid coolant to the chamber at a pressure of between 0 to 100 Bar. Preferably, the jet of liquid coolant is supplied to the second nozzle at a pressure in excess of 40 Bar.

Optionally, the jet of liquid coolant to clean the wheel is directed at a point spaced from the contact zone. Preferably, the second nozzle means is arranged to direct a jet of liquid coolant away from the grinding contact in a substantially radial direction to the wheel.

It is most preferred to incorporate a zoned control of coolant delivery to the interior of the wheel.

Unlike the externally applied coolant-jet cleaning (which can take place almost anywhere on the wheel periphery) the cooling and lubricating effect of the internal coolant should be controlled and aimed into the contact zone. As the contact zone may change (anywhere within 300° radial arc) it is important to control the point of exit. Also the rotational speed of the wheel affects the coolant point of exits from the slots.

There are preferably four zones that can be used in any combination to ensure the point of contact is always kept flooded with coolant. Depending on wheel rotational speed and point of contact the appropriate zone or zones can be switched on through a machine control to ensure the contact zone is always flooded.

According to a further optional feature of this aspect of the invention, there further comprises a controller to control the rotational speed of the grinding wheel and select a contact zone to supply the liquid coolant.

The grinding wheel may be composed of diamond bonded abrasive wheel in either a resin, galvanic, vitrified or metal bonded construction.

A second aspect of the invention comprises a method of carrying out a grinding operation on a work piece at a high material removal rate including the steps of (i) setting up the grinding wheel for a series of cuts of potentially different depths either "up cut" or "down cut" grinding; (ii) selecting the nozzle zone; (iii) setting up the apparatus to direct liquid coolant at the grinding contact point; and (iv) grinding the work piece by rotating the grinding wheel at peripheral speeds in excess of 10 m/s. There may further comprise the step of moving the table speed in excess of about 2 m per minute.

A third aspect of the invention provides a controller for controlling high speed grinding apparatus, which controller comprises a central processor, a manual input means and separate means controlled by said central processor for controlling individually the liquid coolant supply to the delivery means at the point of grinding contact and/or to clean the grinding wheel. Preferably, the means for controlling the liquid coolant supply is a matrix of valves within the liquid coolant delivery system.

A fourth aspect of the invention provides a control system for controlling the operation of an apparatus comprising the steps of (a) activating the liquid coolant supply; (b) selecting rotational speed of grinding wheel; (c) selecting the nozzle zone (d) activating grinding cycle; and (e) terminating the liquid coolant supply.

A fifth aspect of the invention provides or permits automated nozzle setting. In use during grinding, it is preferred that the coolant nozzle assembly can be moved out of the way to allow a change of tool or wheel and then reset for the next grinding or profiling operation upon the workpiece. A preferred construction of apparatus incorporating automated nozzle setting includes a 2-axis motion to lower the nozzle out of the wheel, then rotate the nozzle 90° (to be clear of the tool change zone). Once the tool or wheel has been changed (using a

machine tool magazine loaded with a plurality of different profiled wheels) the nozzle is then rotated back through 90° and lifted into its working position.

Exemplary embodiments of the invention will now be described in greater detail, by way of example only, with reference to the arrangements illustrated in the accompanying drawings in which:

FIGURE 1 is a schematic diagram illustrating one embodiment of the invention;

FIGURE 2 is a top plan view illustrating alternative positions of the coolant nozzle;

FIGURE 3 is a perspective view of a fifth embodiment of the invention;

FIGURE 4 is a cross section view of the grinding wheel assembly of the embodiment shown in Figure 3; and

FIGURE 5 is a flow diagram illustrating one embodiment of the controller for controlling the grinding wheel and delivery means.

For the purpose of illustrating the principles of a grinding process incorporating the invention, Figure 1 shows a grinding apparatus according to one embodiment of the invention. The grinding apparatus comprises a grind wheel 10 rotating in the direction of arrow 16 (Figure 2) while a workpiece 11 is fed past the wheel 10 in the relative direction of arrow 17. In the illustrated example, this produces an operation known in the art as "down" grinding in a contact region generally indicated as 9, whereby the grinding action occurs during the downward movement of the grinding wheel relative the workpiece. Of course, the apparatus can operate an "up" grinding process without departing from the scope of invention.

Essentially the process of the invention is to grind a feature in one or more passes, using a set of parameters (set out below) to facilitate the highest possible material removal rate, whilst producing the workpiece to a satisfactory geometric and metallurgical condition. The workpiece to be machined is fixed to a surface table, which is fed past the rotating grinding wheel at a constant speed. The material removal rate is set by the cutting depth and the

transverse speed. This is determined in combination with a number of other variable factors, for example, peripheral speed of the grinding wheel, the grinding wheel specification, the size and type of profile being machined, the coolant type, pressure and flow available. It is envisaged these factors are variable according to the requirements of the ground component.

The type and composition of the wheel is chosen for the type of material to be ground for the most acceptable balance between material removal rate and wheel wear.

Turning again to the embodiment of Figure 1, the grinding wheel 10 is mounted on a rotary spindle 8 carried by a tool head or chuck 7 which may be part of a standard multi-axis machine, or any other machine adapted to carry out the process. The workpiece 11 is held by means of a mounting fixture 12 and can be moved in up to five degrees of freedom. Preferably, the mounting fixture 12 is mounted on a rotary axis table 13, which in turn is mounted on a tilt axis 14.

The wheel is capable of running as a multi-pass process, although it is primarily intended to be a "one-pass" grinding process, so the width of the grinding wheel is, of course, determined by the corresponding width of the ground surface required. No significant variation of results have been found using grinding wheels in a preferred width range of 3 mm to 50 mm providing the surface speed is maintained constant. Of course, other widths of wheel can be used without departing from the scope of invention and the invention may be expected to produce beneficial results regardless of the width of the grinding wheel.

In a preferred embodiment, the range of values of surface speed for the type of grinding wheel employed is from about 30 metres per second up to about 100 metres per second. Wheels of various diameters give consistent results providing surface speed is matched with the other parameters described above. In the illustrated embodiment, the diameter of grinding wheel used is up to approximately 300 mm, although the diameter of the wheel could be larger by adjusting the machinery to maintain physical clearance in the operative region of the machine.

It is preferred to use a diamond bonded abrasive wheel of either resin, galvanised, vitrified or metal bond. Such super abrasive grinding wheels that utilise a metallic construction are usually only limited in their rotational speed by machine tool constraint.

The embodiment shown in Figure 1 further comprises a coolant system to direct a jet of coolant at high pressure to the point (or zone) of grinding contact. The jet of liquid coolant, preferably water-soluble oil, is directed through nozzle 5 at an aiming point 19 on the periphery wheel 10. The nozzle 5 is the outlet of a closed-loop coolant delivery, collection and filtration system. Spent coolant ejected from the wheel is collected in a sump 15, in the lower part of the machine, and drawn-off through a filtration system 1 to remove debris of a particle size, typically in excess of 0.05 mm.

Integral with the filtration system 1 is a high-pressure pump system 22a, which delivers coolant under pressure through outlet means 4 to the delivery nozzle 5, which nozzle is detachably connected to the outlet means. In the illustrated embodiment the coolant supply is delivered via the outlet 4 at a pressure of up to 100 bar, typically 70 bar, at a flow rate of between about 60 and 120 litres per minute. A significant improvement is achieved by using a coolant delivered within a range of pressure from about 30 Bar to about 100 Bar.

The nozzle 5 is positioned close to the periphery wheel 10 to deliver the high-pressure jet 18 of coolant at the wheel in a substantially radial direction to the wheel circumference at a point outside the contact zone on workpiece 11. The nozzle 5 is constructed and arranged to direct a jet of coolant fluid in a direction perpendicular to the periphery of the wheel at the impact point across the full width of the wheel.

The nozzle 5 outlet design, size and shape will vary according to wheel profile, and desired pressure and flow of coolant. Thus, the orifice can direct a jet of coolant in the shape of a sheet, fan or cylinder at the periphery of the wheel to obtain substantially even distribution of coolant across the width of the wheel.

If a wheel 10 of different width is employed the coolant nozzle 5 is also changed to match. For example, where a grinding wheel much wider than the width of a single nozzle is used, then two such nozzles may be mounted side-by-side to produce a combined cleaning jet spanning the whole width of the wheel. In some embodiments, two nozzles are preferred to a single double-width nozzle to avoid the need to change the nozzles to suit the wheel, because in a double nozzle arrangement one of the nozzles may be fed through an on-off valve so that

when a narrower wheel replaces the wider one, then the supply to one of the nozzles is turned off to avoid wastage.

Figure 2 shows three possible positions A, B, C to position the nozzle 5 so that the impact point of the jet is proximate the grinding point. A pair of convergent lines 20, 21 shows the excluded angle between these two lines 20, 21 to define the circumferential position of the impact point of jet 18. The primary function of nozzle 5 is to clean the surface of the grinding wheel to ensure the abrasive grain is as clean as possible when it reaches the contact region 9.

Additionally, or alternatively, there is further provided a second high pressure pump system 22a integral with the filtration system which delivers coolant under pressure through a second outlet means 3 to a second delivery nozzle 6. In the illustrated embodiment, the coolant supply is delivered via the outlet 3 at a pressure of up to 100 bar, typically 70 bar, at a flow rate of between about 60 and 150 litres per minute. For illustration purposes, two high-pressure pumps 22a and 22b have been shown but a single larger pump could be used instead.

The purpose of nozzle 6 is to deliver a high-pressure jet 26 of coolant to quench or cool the component and/or lubricating the contact zone at or very close to the contact region 9. This is achieved by directing the coolant nozzle 6 in one of four ways.

In the first embodiment shown in Figure 1, the coolant nozzle 6, operating in one of the preferred ways of coolant delivery, delivers the coolant into the rotary spindle by aiming the coolant nozzle 6 at the rotary spindle 8. The rotary spindle 8 is manufactured with a plurality of slots 28 and a central chamber (not shown) to allow coolant to flow into it and direct coolant down to the grinding wheel 10. The grinding wheel 10 incorporates internal channels 29 allowing the coolant to flow to the periphery of the wheel.

Alternatively, a second embodiment using a "through spindle coolant" delivery process is used. The delivery is achieved by passing coolant through the centre of the tool head 7, through the rotary spindle 8, and is carried under pressure and through centrifugal force to the periphery of the wheel via internal channels within the grinding wheel. The volume of coolant required to achieve the desired affect of cooling and lubricating is dependent upon,

among other variables, the size of the wheel 10 (both diameter and width), the wheel speed and the feed rate of the material 11 through the contact area 9.

A third embodiment employs a coolant delivery process which is achieved by aiming the coolant nozzle 6 onto the top surface of the grinding wheel 10 and optionally from underneath to supply coolant into the wheel cavity. The grinding wheel 10 is manufactured with an exposed cavity that collects the coolant and the construction of the wheel would allow the coolant to flow through to the periphery. This enables the contact area 9 to be cooled and lubricated as required.

A fourth embodiment uses a process shown in Figure 2. For simple profiles on the grinding wheel the high-pressure coolant jet 24 or 26 could be delivered at the wheel 10 circumference at a point inside the contact zone indicated by 25 and 27 respectively. Depending which of the two points was deemed to be more effective the nozzle 6 would be positioned in one of the two positions 23 as illustrated.

A fifth and more preferred embodiment will now be described by reference to Figures 3 and 4 which shows how a number of coolant supplies are directed into the centre of the grinding wheel, and optionally, a high pressure supply is supplied through a single nozzle 5 onto the external surface of the grinding wheel to assist in cleaning the wheel. The grinding wheel 110 comprises an internal chamber 40 and a plurality of channels 30 for fluid communication between the internal chamber 40 and the external surface 31 of the grinding wheel 110. Preferably the channels are provided by slots, which are approximately 1 to 3 mm wide. In some embodiments, the slots are shaped or angled. Alternatively a mesh is employed, for example in the form of a honeycomb.

The coolant is supplied to the internal chamber 40 by one or more supply pipes and passes through the channels 30 to the point (or zone) of grinding contact.

In this embodiment, there comprise four coolant supply pipes 32, 34, 36, 38. The controller controls the coolant supply to each of the pipes, described in more detail below. Preferably, each of the pipes supplies fluid to a different zone of the internal chamber, so that coolant can be supplied to that part of the wheel that is in grinding contact with the component.

Figure 4 illustrates a cross-section of the grinding wheel 110 in more detail. Channels 42, 44, 46 and 48, which are connected to pipes 32, 34, 36 and 38 respectively, supply the four zones. Preferably the channels 42, 44, 46 and 48 are angled in the direction of rotation of the grinding wheel, so that the coolant is supplied to the internal chamber with minimal resistance to the grinding wheel. The controller uses information, such as the rotational direction and speed of the wheel and the grinding point, to determine and select the appropriate zone to use as the coolant supply. Thus, the supply of the coolant to the internal chamber, and onwards to the periphery of the grinding wheel through the slots, is controlled.

Preferably, a matrix of valves controlled by the controller is used to control supply to the pipes 32, 34, 36 and 38.

Figure 5 illustrates a flow diagram for controlling the coolant system. The controller is provided with a central processor, manual input means through which specific instructions can be programmed and a display, which indicates useful information to the machine operator. The central processor and the display can display and will allow selection of operational information such as the wheel 110, and various other parameters 112 (shown in Figure 5) including the rotational speed of the grinding wheel and the pressure of the or each nozzle. Such information can be provided through sensors or other suitable means known in the art. The controller controls the flow rate of the coolant to the point of grinding contact and/or the rotational speed of the grinding wheel. These parameters 110, such as the position and speed of the grinding wheel coolant system can be input manually or a specific prewritten programme can be loaded into the central processor for control of the apparatus. Also, control of the changeover of the machine from one component to another can be the result of a prewritten programme or manual input signal.

With the "grinding cycle" software, there will be a prompt to allow for the internal coolant supply to be delivered into the centre of the wheel from underneath shown in Figure 4. The prompt will allow selection 100 of one of the four zones or any combination to be used (but this number of four should not be treated as absolute) which is controlled through the valve matrix. The controller will also select 102 the external nozzle 5 and activate it 104 together with the coolant supply 106. The grinding cycle 114 is commenced and the work piece ground into its final form. The cycle is ended 116 and the machine returned to its safe position 118 for removal of the work piece.

By applying this method of coolant application, it is possible to control the area on the periphery of the grinding from which the majority of coolant will flow. By being able to control this, it increases the effect of lubrication and cooling in the contact zone.

Also, with the controller, the display will include a prompt to activate the coolant applied externally to the surface of the grinding wheel. This will be operated via an "M" code within the control system and will automatically switch on the coolant pump.

The present invention is carried into practice in one class of embodiments by using a multi-axis milling machine adapted to operate using a grinding wheel in place of the normal milling cutter. A main reason for using a multi-axis machine of this kind is its ability to reproduce complex surface profiles on the ground workpiece, although this particular topic is outside the scope of the present invention. It is to be understood, therefore, that the relative motions of the grinding wheel and workpiece may be compound movements, notwithstanding that for simplicity the accompanying drawing represents such relative movement as rectilinear. Alternatively, the invention can be supplied and fitted to existing machines on a retrofit basis.

Modifications may be incorporated without departing from the scope of the present invention as defined in the accompanying claims.

Written into the control system will be a "wheel change" routine that will automatically carry out a number of tasks to ensure the "routines" are completed prior to wheels changing. For example, the wheel will stop rotating, the coolant mechanism will move to the "park" position, the coolant pump(s) would stop. This is carried out automatically in an attempt to avoid unnecessary collisions.

The invention, by providing a unique and highly optimised method of coolant delivery, has allowed component "cooling", grinding wheel "cleaning" and contact lubrication to be maximised. In turn this has greatly assisted in achieving very high material removal rates, and good grinding wheel life. By controlling the parameters, we have also been able to control the mechanical loads on component and wheel, and have discovered a small window that allows extreme MMR^s to be achieved.

Preferred embodiments of the present invention provide twin coolant delivery routes from a single coolant delivery mechanism or system.

Accordingly, coolant can be delivered from a series of internal nozzles through slots in the grinding wheel. Coolant can also be delivered simultaneously from a single external nozzle to the exterior of the wheel. From the single mechanism, both an internal and external means of delivering coolant is achieved. The internal coolant can be delivered through the slots in the wheel, aided by centrifugal force. This flow cools and lubricates the contact zone. The external coolant is delivered onto the wheel surface. This flow cleans any debris from the wheel surface. The internal flow is preferably of moderate pressure – up to 30 bar – so as to accelerate the coolant in the general direction of the wheel rotation, and help reduce the hydro dynamic effect. The external flow is of a high pressure – up to 100 bar – so as to hit the surface of the wheel with sufficient impact to remove grinding debris and any other particles that may get stuck in the wheel surface. This is known as 'jet cleaning,' it keeps the abrasive particles clean and enhances grinding performances.

Such preferred embodiments of the present invention can thus provide a novel method of internal zoned coolant delivery which permits an almost infinitely variable number of wheel profiles to be simultaneously cooled and lubricated from a single coolant delivery system as well as providing the freedom to machine in a zone of the order about 300° of the grinding wheel surface, as distinct from a distinct, fixed point thereon.

Such an arcuate machining zone or 'active machining segment' can be achieved without adjusting or moving the coolant delivery system or components thereof, and this can be achieved without the use of any additional external coolant delivery nozzle beyond the one which is essential which could create extra difficulties by collision with the workpiece. The necessary changes can be made in the machine programmes by modifying the internal coolant zones in use.

In use of preferred embodiments of machine according to the invention, utilising a combination of internal coolant delivery, high pressure external jet cleaning then by selecting appropriate wheel speed, table speed and cutting depth, we have found it possible to grind titanium and titanium alloy materials to a burn-free, good quality surface at MRR of up to 50

mm^3/mm/sec which compares favourably with other known grinding techniques typically providing MMR in the region of 2 to 3 mm^3 for titanium materials.